Increasing efficiency of ecological vehicles by integrating auxiliary units directly to the traction shaft

N. Satheesh Kumar
Interdisciplinary Graduate School
Nanyang Technological University
50, Nanyang Avenue, Singapore 639798
Email: ns0001ar@e.ntu.edu.sg

Dr. Michael Schier
Institute Of Vehicle Concepts
German Aerospace Center
Pfaffenwaldring 38-40, D 79569 Stuttgart, Germany
Email: michael.schier@dlr.de

Abstract— **The climatisation requirements of Electric Vehicles (EVs) largely depend on its usage location. For example, EVs operated in European countries require heating during the winter season, while those operated in equatorial regions face cooling load throughout the year. To date, the low range for a given battery charge remains the single-most important factor hindering the widespread acceptance of EVs. The principal electrical loads of an EV comprises of the traction and air-conditioning (A/C) compressor motors. These high power loads expedites the battery drain, leading to poor cruise range. The paper proposes a novel design solution geared towards improving the overall operating efficiency of these motors by integrating them into a single housing.**

The integrated unit is expected to operate close to 100 % efficiency during recuperation mode. The unprecedented improvement in efficiency is achieved through direct mechanical coupling of the traction motor with the A/C compressor during breaking events. The mechanical configuration of the unit is such that the torque and speed characteristics of traction and compressor motors can be independently controlled during drive mode. In addition to improved efficiency, the integrated unit boosts numerous other advantages such as increased reliability, compact design and weight saving.

Keywords—climatisation; regenerative braking; electric vehicle; integrated drive; A/C compressor; mechanical clutch .

I. Introduction

In recent years, increasing concern over climate change has provoked the automotive industry to reconsider EVs as a viable candidate to replace vehicles powered by Internal Combustion (IC) engines. Over the years, unparalleled advancements in EV technology have enabled them to operate at higher efficiency and longer maintenance intervals. Nevertheless, the market penetration of EV is comparatively low, due to its poor performance characteristics, as opposed to IC powered vehicles.

The novelty of this project is to design and verify a concept for integrating the A/C compressor with the traction motor of an EV. One of the challenging issues of the project is to discover an innovative system that conforms to the compressor's requirements of power and torque while the vehicle's traction motor is running at an independent speed.

II. Literature Review

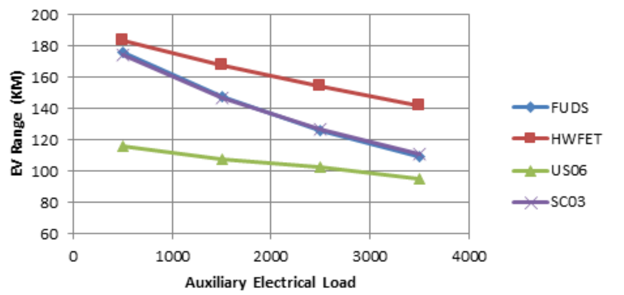


Fig. 1: Impact of auxiliary electrical load on EV's range for various drive cycles [1].

Farrington and Rugh [1] provided a comprehensive insight into the detrimental impact of an auxiliary electrical load on the range of electric vehicles. The study simulated a five-passenger EV powered by NiMH battery using ADVISOR (Advanced Vehicle SimulatOR). The flexibility of the simulation platform allowed scheduled application of the auxiliary electrical loads based on U.S EPA certification procedures: FUDS, HWFET, SC03 and US06. To appreciate the significance of the findings, consider an EV operating in SC03 drive cycle with a base electrical load of 500 W. Switching on a 1500 W A/C will increase the auxiliary electrical load to 2000 W, which drastically slashes the EV's cruise range by 22 % (Fig. 1).

The paper identified the A/C as the single largest electrical load that leads to a drastic reduction in vehicle's range. In addition, the authors conclude that a marginal improvement in air-conditioning efficiency would result in a huge impact in energy savings due to the volume of new EVs sold each year.

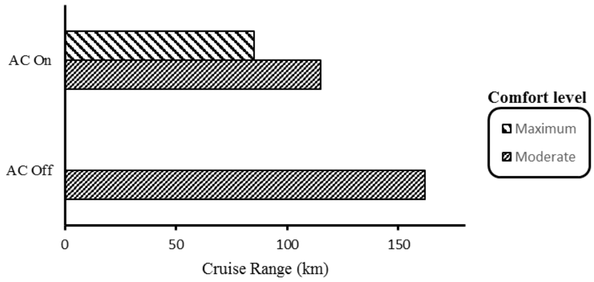


Fig. 2: Impact of A/C on i-MiEV's cruise range [2]

On average, an automobile is driven for 250 hours per year [3]. This roughly equates to 115 hours of A/C operation [4], corresponding to 45 % of the vehicle usage. The A/C system in an EV acts as a parasitic load, as the system draws in energy only when the passenger chooses to turn it on. Such an electrical load is often termed as "off-cycle" electrical load. Other off-cycle loads include wipers, stereo systems, heated seats, headlight, and defrosters. Although these loads tap into the battery power, the A/C system is unique as it puts on a considerably larger electrical load. This strains the battery and results in rapid depletion of the stored energy. In fact, it is estimated that the use of air conditioning typically causes an approximate 33 % decrease of the EV's range [5].

In another study [2], Mitsubishi Motors subjected its recent EV: i-MiEV on number of tests to measure the drop in cruise range due to the operation of A/C. The maximum cruise range of the vehicle was established by conducting the first run with A/C turned off. In the subsequent runs, the A/C unit was operated with moderate and maximum settings to determine its effect on the cruise range. Based on the plot (Fig. 2), it can be deduced that cruise range decreases by 30 % when A/C is operated with moderate settings and by a staggering 48 % when operated with maximum settings.

Gui-Jis Su [6] explored the concept of electronic integration of the traction and compressor motors. The motive for such an integration is to reduce component count, minimize cost and the overall size of the compressor motor. With reference to Fig. 3, Gui-Jis Su explains that in a conventional system, independent inverters control the traction and the compressor motors. In this case, two three-phase motors and inverters are required for a trouble-free operation and independent speed regulation of the motors.

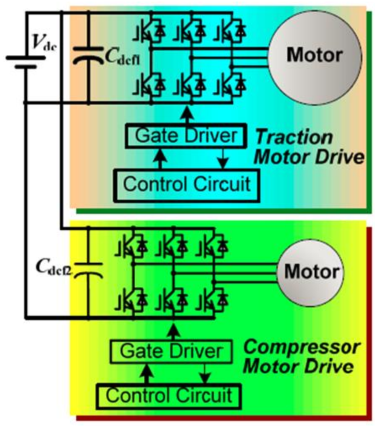


Fig. 3: A conventional configuration of traction and compressor motors controlled by independent inverters [6]

Gui-Jis Su proposed replacing the three-phase compressor motor with a low-cost two-phase motor and inverter. Comparing Figs. 3 and 4, it can be noted that the electrical integration of the two-phase inverter with that of the three-phase inverter results in fewer parts and allows the possibility of sharing the DC bus filter capacitor and gate drive power supply system. In general, the circuit decreases the manufacturing cost, time and slashes the component count by one-third.

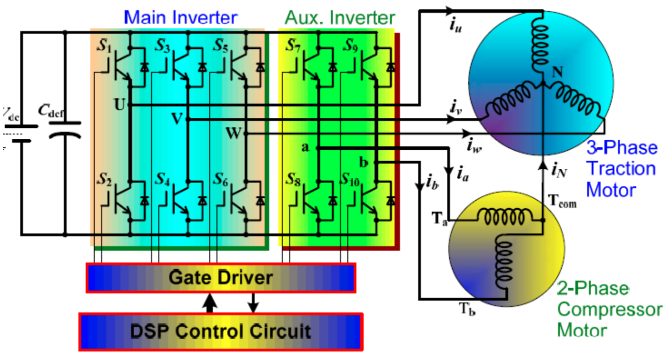


Fig 4: Electrically integrated traction and compressor motors [6]

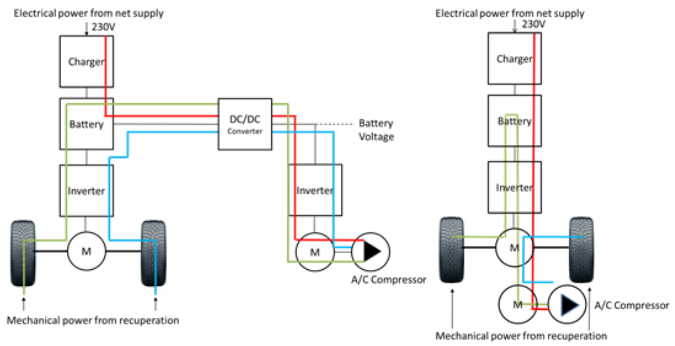
Apart from electrical integration, the traction and compressor motors can be physical integrated for number of other reasons. The advantages of physical integration include:

- elimination of a separate cooling systems for each motors
- minimises external electrical cable
- weight and space saving
- reduced parts count and increased reliability

These advantages are attractive for the automotive industry as it enables the EVs to operate at higher efficiency, improved reliability and decreased maintenance and manufacturing cost.

III. ASSESSMENT

Fig. 5(a) illustrates the energy flow structure of the A/C compressor in a conventional EV. As depicted in the illustration, A/C compressor can receive electrical power from three distinct sources (indicated by three solid lines). The three possible energy flow paths are explained in greater depth:



(a) Conventional configuration (b) Proposed configuration

Fig. 5: (a) Power flow path in a conventional system (b) Power flow path in proposed system

- the red line in the Fig. 5 represents the first source. This source provides the power to operate the motors from an external power network. This power flow path provides the electrical energy to the A/C compressor regardless of whether the EV is driving, braking or stationary.
- the green line describes the flow of energy when the A/C compressor is powered from the battery. The power to recharge the battery could either provided by the external net or the energy recovered during recuperation mode. During recuperation mode, the vehicle's forward momentum is captured and transformed into electrical power by the traction motor. This recovered electrical energy is stored in the battery for later utilization.
- the blue line illustrates the active recuperation mode. This power flow path bypasses the battery and connects the drive motor with the compressor. The power to operate the A/C compressor is supplied directly from the recuperated energy from the current braking event.

The key differences between the conventional and proposed system include: (1) shared inverters, (2) elimination of DC/DC converter and (3) possibility to mechanical couple the traction motor with compressor motor during active recuperation mode. To estimate the efficiency of the conventional and proposed system, the system components are modelled as energy converters having the efficiencies listed in Table 1. Note that both the best and worst case efficiencies are reported and the mean value was used for subsequent calculations. As stated by the Eq. (1), the efficiency of a given energy path is obtained by multiplying the efficiencies of the components which make up the energy flow path.

$$\eta_{energy\ path} = \Pi_i^N \eta_{component_i} \tag{1}$$

TABLE 1: EFFICIENCY OF INDIVIDUAL COMPONENTS

Type of Energy Converter	Efficiency		
	Best case	Worst case	Average value
Charger	0.95	0.90	0.93
Battery	0.95	0.70	0.83
Inverter-Drive Motor	0.95	0.85	0.90
Motor - Drive	0.95	0.90	0.93
DC/DC Converter	0.95	0.90	0.93
Inverter - Compressor	0.95	0.85	0.90
Motor - Compressor	0.95	0.85	0.90

Following Eq. (1), it is approximated that the conventional system operates with a net efficiency of 62 % during recuperation mode while the proposed configuration attains an efficiency close to 100% for the same mode.

The recoverable power obtained from a car with mass m, and travelling at initial velocity v, can be calculated by:

$$P_{gen} = \frac{\eta_{gen} \cdot m \cdot v^2}{2 \cdot t} \tag{2}$$

Where η_{gen} represents the generator efficiency and t represents the total braking time.

Typically, the maximum generated power ($P_{gen,max}$) during recuperation mode is limited to the driving power of the motor. This ensures that the traction motor operates within its safe electrical limits. Therefore, it is favorable to use electric motors with large power ratings to maximize the recoverable energy.

The average $\bar{P}_{gen}$ can be calculated if the total braking energy ($E_{braking}$) and time are known:

$$\bar{P}_{gen} = \frac{E_{braking}}{t_{total}} \tag{3}$$

Based on the power rating of the motor, the maximum braking torque can be computed by:

$$T_{braking,\max} = \frac{P_{gen,\max} \cdot 60}{2\pi N} \tag{4}$$

where N represents the motor speed in RPM.

In urban settings, the heavy traffic coupled with a concentration of traffic lights results in frequent breaking events. This provides immense potential to recuperate the energy required for direct driving of the A/C compressor. A quantitative analysis was performed in ADVISOR to determine the maximum recoverable energy for various European drive cycles applicable for cars. For the purpose of investigation, a mid-size electric car powered by NiZn battery and with a mass of 1008kg was modelled in ADVISOR. Following that, the car was simulated at various drive cycles to determine the total braking energy ($E_{braking}$) and time (t) for each drive cycle. The average P_{gen} was calculated using Eq. (3). The results of the study has been presented in Table 2.

TABLE 2: PERCENTAGE BRAKING TIME AND AVERAGE P_{GEN} FOR VARIOUS DRIVE CYCLES

Drive cycle	**Distance travelled (km)**	**Total time (sec)**	**Braking time (sec)**	**% braking time**	**Average P_{gen} (kW)**
ECE 15	1.0	195	39.4	20.5%	1.5
EUDC	7.0	400	45.0	11.3%	2.9
EUDC, low power	10.6	1224	101.0	8.3%	3.8
ECE 15 + EUDC	10.9	1225	202.1	16.5%	1.9
NEDC	10.9	1184	201.3	17.0%	1.8

With reference to Table 2, aggressive drive cycles such as ECE 15, ECE 15+EDUC and NEDC have a substantial period of braking events. By average, a vehicle spends close to 15 % of its total time in braking, signifying an immense potential for energy recuperation for all drive cycles.

A mid-size car with a moderate heat infiltration have a cooling load requirement of 5 kW. Automobile compressors typically operate with a COP of 3. Since the proposed unit is able to recuperate close to 100 % of the energy, a compressor with a power load of 1.6 kW (based on Eq. (5)) will be able to operate solely on the recuperated power throughout the drive cycle while meeting the climatisation requirement.

$$Compressor\ power = \frac{Cooling\ Load}{COP} \tag{5}$$

IV. DESIGN

Based on Fig. 5(b), the proposed system configuration calls for a design that permits the traction and compressor motor to operate independently through a shared inverter, with a provision to directly transfer recuperated energy from the traction motor to the A/C compressor. The torque generated by the traction motor is used to operate the vehicle whereas a dedicated motor is used to drive the A/C compressor. The use of an independent motor for the compressor allows for a continuous and infinitesimal control over the compressor's capacity through speed variation. However, these motors have to be mechanically coupled during braking events to recuperate the vehicle's forward momentum to drive the A/C compressor. The immediate utilization of the recuperated energy will minimize the energy flow path, leading to increased efficiency.

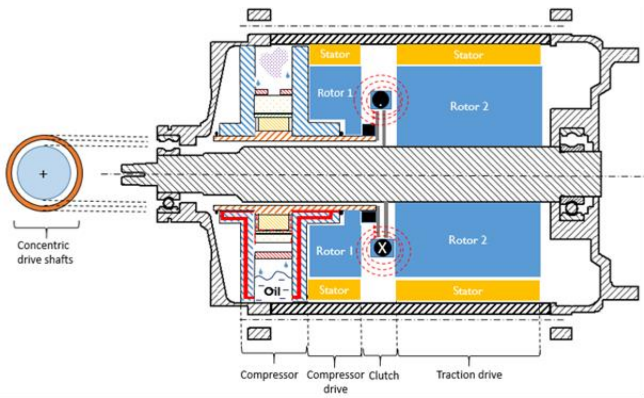


Fig. 6: Concept of the integration of an air conditioning compressor into the drive motor of an electric vehicle

Fig 6 illustrates the schematic diagram of a design, satisfying the proposed system configuration. The design uses concentric shafts to achieve coaxial placement of the traction and compressor drives. This arrangement provides the flexibility of independent torque and speed control of the drives (traction and compressor). Hence, the A/C compressor can be operated at full capacity while the vehicle is at a complete stand still. The electromagnetic clutch kicks into action during braking events. When the brake is applied, the clutch plate physically connects the traction drive with compressor drive, which facilitates the recovered car's forward momentum to be used in powering the A/C compressor. This short-circuits the energy flow path that results in nearly 100 % of the recuperated energy to be used in driving the A/C compressor.

Primarily, there are four different types of compressors suited automotive application: Scroll compressor, wobble plate compressor, swash plate compressor and rotary piston compressor [7]. The rolling piston compressor is widely favored by the industry due to its simple design, high reliability, and efficiency. However, the rotary piston compressor suffers from large frictional and leakage losses incurred by the vane rubbing over the rotating piston. These losses negatively affect the cooling capacity and volumetric efficiency of the compressor. To address this issue, a new type of rotary piston compressor was introduced by Dikin, named "Swing Vane Compressor (SVC)". The SVC is similar to rotary compressor, except for the fact that the vane is rigidly attached to piston body, thereby eliminating all leakage and frictional losses between the vane tip and the piston. Consequently, the new design variant resulted in increased efficiency. The proposed design will use a modified variant of SVC which is expected to further enhance the efficiency of a convention SVC.

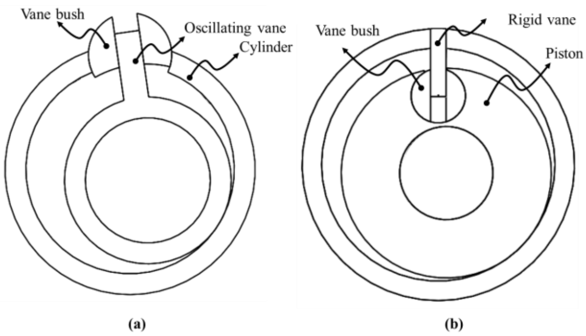


Fig. 7: (a) Conventional SVC, (b) Modified SVC

Fig. 7 compares the conventional and modified SVC. A conventional SVC has an oscillating vane while the modified SVC has its vane rigidity held against cylinder wall. This reduces the frictional losses between the vane bush and the vane as the contact force between these components are no longer a function of pressure difference acting on the exposed vane surfaces.

V. Design Implementation

An existing EV's induction motor will be modified to verify the feasibility of the proposed design and access the practical efficiency gains. This strategy will facilitate easier installation after modifications as the existing motor interfaces with the vehicle can be preserved while design changes are confined to the interior of the motor.

Fig. 8: The EV to be used as a test bench

The motor specifications of the test bench vehicle (Fig. 8) are listed in table 3. The stator and rotor of the current traction motor has to be downsized to provide space for the compressor and its drive motor. Hence, the power density of the traction motor will be increased by using a permanent magnet excited synchronous machine to prevent degradation in the performance characteristics of the vehicle. In addition, the cooling fins of the air cooled motor will be replaced with a water jacket to prevent a thermal run-away due to the increased heat liberation from the A/C compressor and high power density motors.

TABLE 3: EXISTING MOTOR SPECIFICATIONS

Parameters	Value
Power	12 kW
Speed	5920 RPM
Number of slots	36
Number of poles	2

VI. Conclusion

Cabin climatisation and high cruise range are the key features required to increase the market penetration of EV. However, studies reveal that climatisation has an immense impact on the range performance of the EV. Tests conducted on i-MiEV identified a drastic drop in the cruise range by a staggering 30 to 48 % when operate with moderate and maximum cooling settings respectively. The result coveys the necessities to identify a means to enhance the efficiency of A/C to mitigate its impact on the cruise range of the EV.

The paper described a novel system configuration that will increase the efficiency of the power delivered to the A/C system during recuperation mode. The initial assessment predicts that nearly 100 % of the recuperate energy can be delivered to the A/C compressor during braking events. The immediate utilization of the recuperated power to drive the compressor will translate to increased overall efficiency.

The paper offered a design solution to fulfill the requirements of the proposed system configuration. The design uses concentric shafts of the compressor and traction motors to enable the unit to fulfill fluctuating torque-speed requirements of both the vehicle and the compressor without any interference. The principal novelty of this invention steams from its ability to mechanically clutch the A/C compressor motor with the traction shaft during braking events. The unit elegantly integrates a design variant of the swing vane compressor to attain efficiency gains during compressor operation.

The proposed invention fulfills the requirements of providing traction and cabin climatisation of electric vehicles, thus represents an important milestone in the development of highly integrated unit manufactured using fewer and smaller components. Regardless of drive cycle, it is expected that the invention will result in improved efficiency that ultimately translates to increased cruise range. A prototype will be manufactured and mounted on a test vehicle to verify the feasibility and practicality of the invention.

Acknowledgment

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